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The growth of the nuclear black holes in submillimeter galaxies

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ABSTRACT
We show that the ABC scenario we proposed for the co-evolution of spheroids and QSOs predicts accretion rates and masses of supermassive black holes in sub-mm galaxies in keeping with recent X-ray determinations. These masses are well below the local values, and those predicted by alternative models. The observed column densities may be mostly due to ISM in the galaxy. The contribution of the associated nuclear activity to the X-ray background is likely negligible, while they may contribute a sizeable fraction $\sim 10\%$ to hard-X cumulative counts at the faintest observed fluxes.

Key words: galaxies: formation galaxies: active cosmology: theory - X-rays: galaxies

1 INTRODUCTION

In recent years, many efforts have been devoted to understand the population of high-z galaxies detected by submillimeter surveys (SMGs), which could dominate the $z > 2$ cosmic star formation (SF), and may pinpoint the major epoch of dust-enshrouded spheroid formation, as suggested by the their SF level, high mass fraction, large dynamical mass and strong clustering (Smail et al. 1997, Hughes et al. 1998; Barger et al. 1998; Blain et al. 2004; Greve et al. 2005).

From the theoretical side, the ΛCDM cosmology is a well-established framework to understand the hierarchical assembly of dark matter (DM) halos, but the complex evolution of the baryonic matter remains an open issue, because whatever simulation must include huge simplifications for its physics. Unfortunately, these simplifications pertain processes which are major drivers of galaxy evolution, such as SF, feedback and nuclear accretion.

The class of computations known as semi-analytical models (SAM) have been extensively compared with a large range of observations at various redshifts. Besides many successes, some difficulties persist in standard SAM, broadly connected with massive galaxies (e.g. the color-magnitude relation, the $[\alpha/Fe] - M$ relation, the statistics of sub-mm and deep K-band selected samples: see Thomas, Maraston, & Bender 2002; Pozzetti et al. 2003; Sommerville 2004; Baugh et al 2005, Nagashima et al 2005). However, the general agreement of a broad variety of data with the hierarchical scenario for DM and the fact that the observed number of luminous high-redshift galaxies, while substantially higher than predicted by standard SAMs, is nevertheless consistent with the number of sufficiently massive DM haloes, indicate that we may not need alternative scenarios, but just some new ingredients or assumptions for visible matter.

In Granato et al. (2001) we suggested that a crucial ingredient to keep into account is the mutual feedback between spheroidal galaxies and the AGN at their centers, largely ignored by simulations at that time, and often even now. This despite the fact that since long observation have suggested a connection between SF and AGN activity (e.g. Sanders et al. 1988), the possible importance of the feedback from the central BH has been discussed (among the first Ciotti & Ostriker 1997; Silk & Rees 1998; Fabian 1999), and its growth has been considered in models for galaxy formation (e.g. Kauffman & Haenelt 2000; Archibald et al. 2002). In Granato et al. (2004, GDS04 hereafter) we presented a physical model for the early co-evolution of the two components, in the framework of the hierarchical ΛCDM cosmology and based on the semi-analytic technique. In our model, the SMGs are interpreted as spheroids observed during their major episode of star-formation (SF). The development and duration of this episode is affected not only by supernova (SN) feedback, but also by the growth by accretion of a central super massive black hole (SMBH), *favored by the SF itself*, and by the ensuing feedback by QSO activity, and completes earlier in more massive objects[1]. Thus the high redshift QSO activity marks and concur to the end of the major episode of SF in spheroids.

The scenario by Granato et al. (2001) and GDS04 is based on a circular relationship between SF and AGN ac-

[1] Thus we named our scenario *Anti-hierarchical Baryon Collapse - ABC*; from the observational point of view the same phenomenon is now commonly referred to as *down-sizing*

tivities, which establishes a well defined sequence connecting various populations of massive galaxies: (i) virialization of DM halos; (ii) vigorous and rapidly dust-enshrouded star formation activity, during which a central SMBH grows; (iii) QSO phase halting subsequent star formation and (iv) essentially passive evolution of stellar populations, passing through an Extremely Red Object (ERO) phase. As detailed by GDS04 and Silva et al. (2005), this scenario fits nicely two important populations at high redshift, which are instead problematic for most semi-analytic models (e.g. Sommerville et al. 2004): vigorously star-forming, dust-enshrouded starbursts (in practice SMG; stage (ii)) and ERO (stage iv). Also, the local luminosity function of spheroids and the mass function of SMBHs are well reproduced. The general consistence of this sequence with high redshift QSO population has been investigated by Granato et al. (2004), while a detailed analysis will be presented by Lapi et al. (in preparation).

In this paper we focus on the model behavior during the SMBH growth in stage (ii), as traced by X-ray observations of sub-mm selected sources. Alexander et al. (2003, 2005a, 2005b) have investigated the X-ray properties of bright SMGs ($S_{850\mu m} \gtrsim 4$ mJy), by combining ultra-deep X-ray observations (the 2 Ms CDF-N) and deep optical spectroscopic data of SMGs. They have found evidence for the presence of mild AGN activity in a large fraction of bright SMGs ($\sim 50\%$), which in our scheme is the signature of this growth, that afterwards will quench the SF, and cause an almost passive evolution of stellar populations.

Recently sub-grid treatments of SMBH growth and its feedback has been implemented in numerical simulations of DM halos and large-scale SPH gas dynamics (e.g. Springel, Di Matteo, & Hernquist, 2005), or in the semi-analytic post-processing of the Millenium DM simulation (Croton et al. 2005, Bower et al. 2005). However, in the latter cases, the feedback role of AGN is limited to the 'radio mode', which suppress cooling flows in clusters at z $\lesssim$ 1.

2 THE GDS04 MODEL

This paper is based on the SAM presented by GDS04, which follows the evolution of baryons within proto-galactic spheroids through simple but physically grounded recipes. We provide a qualitative summary of the model, deferring the reader to that paper for details.

The treatment of the statistic of DM halos essentially follows the standard framework of hierarchical clustering.

During the formation of the host DM halo, the baryons are shock-heated to the virial temperature; this hot gas cools fast especially in the dense central regions or clumps, and triggers a huge burst of star formation. One of the major differences with respect to most semi-analytic treatments of the evolution of visible matter, is that in GDS04 cool and collapsing gas forms stars without setting in a quiescent disc.

The SF activity promotes the gathering of a reservoir of gas with angular momentum low enough to allow accretion onto a nuclear SMBH. A plausible process is radiation drag, which 'naturally' yields a ratio between SMBH and spheroid mass in keeping with observations. The reservoir gas eventually accretes onto the SMBH, powering nuclear activity. The maximum accretion rate is of the order of the

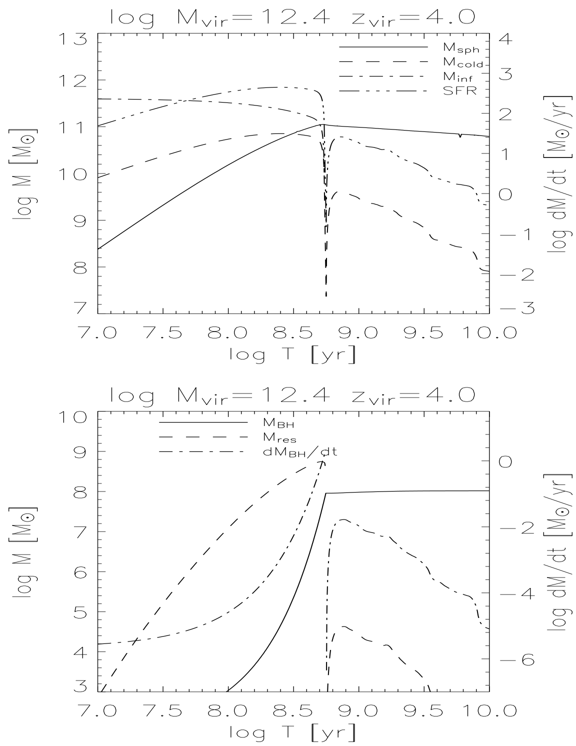

Figure 1. Top panel: evolution of the stellar mass, infalling mass, cold gas mass, and star formation rate within a typical halo of total mass $2.5 \times 10^{12} M_{\odot}$, virialized at redshift 4. Bottom panel: evolution of the BH mass, reservoir mass, and BH accretion rates in the same halo. The discontinuity at $\log T \sim 8.75$ marks the epoch at which the AGN feedback sterilize the system.

Eddington limit, so that the SMBH mass and the BH activity increases exponentially with time. The energy feedback to the gas by SN explosions and BH activity affects the ongoing SF and BH growth. The two feedbacks have very different dependence on halo mass and on time since virialization. The SN feedback is an almost immediate consequence of SF and its time evolution reflects that of SF. It is very effective in low mass halos, severely limiting the growth of stellar and SMBH component, but it is of minor importance in most massive galactic halos; the AGN feedback grows exponentially, it is negligible in the fist ~ 0.5 Gyr in all halos, but suddenly becomes very important in DM halos massive enough to be little affected by SNae feedback. Thus in low mass halos, SNae keep the SF at low level, also limiting the growth of the SMBH and its capability to influence the system. In moderate to high mass halos (see Fig 1), the SNae becomes increasingly less effective, the SMBH can grow efficiently and after a time delay ~ 0.5 Gyr, required by the exponential growth, quenches any further substantial SF, and ultimately its own activity. Since after this point the SMBH is already present at the galaxy center, any subsequent supplying of gas (e.g. due to merging or accretion of the halo) produces an immediate AGN feedback, and thus is unable to alter substantially the star and SMBH mass: the stellar populations evolve largely in a passive way.

Before the peak of the accretion, the SMBH is likely to be obscured by the surrounding galactic ISM, therefore it could possibly be detected only in the hard-X rays while

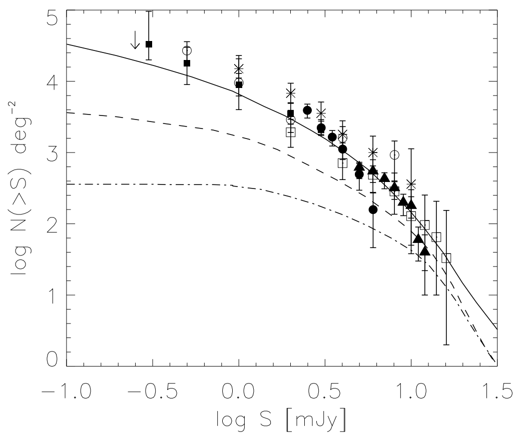

Figure 2. Number counts predicted by the GDS04 model for SCUBA sources with accretion rates greater than two interesting thresholds. Solid: all sources; dashed line: $\dot{M} > 0.013 M_{\odot} \mathrm{yr}^{-1}$ ($L_{\mathrm{bol}} \gtrsim 10^{43} \mathrm{erg\ s}^{-1}$); dot-dashed line: $\dot{M} > 0.13 M_{\odot} \mathrm{yr}^{-1}$ ($L_{\mathrm{bol}} \gtrsim 10^{44} \mathrm{erg\ s}^{-1}$). Data from Blain et al. (1999; open circles and upper limit), Eales et al. (2000; filled circles), Chapman et al. (2002; asterisks), Cowie et al. (2002; filled squares), Scott et al. (2002; filled triangles), Borys et al. (2003; open squares).

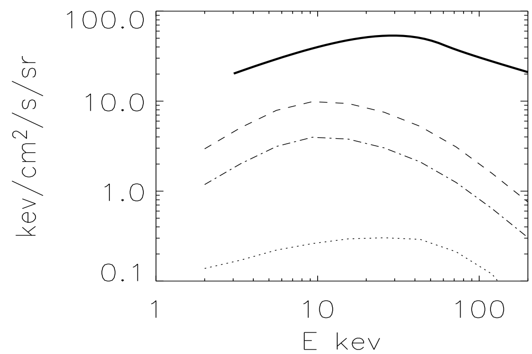

Figure 3. Predicted X-ray background from growing SMBH in all forming spheroids (short dashed line), and from those in SCUBA sources brighter than 1 mJy (dot-dashed line). We adopted $\log N_H = 23.5$ (see discussion in the text). The dotted line is the estimated contribution from stellar populations computed with GRASIL (Silva et al. 1998, 2003). The data (thick solid line), are those adopted by Ueda et al (2003).

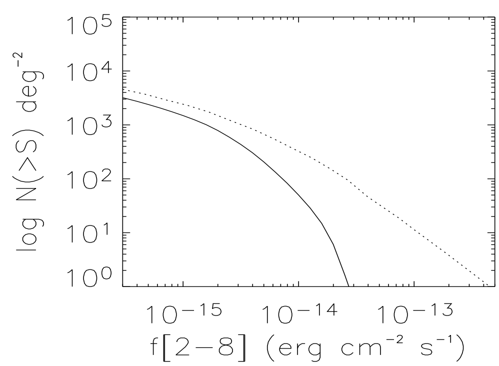

Figure 4. Contribution to the X-ray number counts by growing SMBH in forming spheroids according to the model (solid line). In the computation we have adopted a reference value of $\log N_H = 23.5$ (see discussion in the text). The dotted line outline the observed counts from various sources (Gilli 2003).

the proto-galaxy appears as a SMG: *the present paper is precisely devoted to study this pre-qso phase*. Later on, in the proximity of the peak, i.e., when the central SMBH is powerful enough to remove most of the gas and dust from the surroundings, the system will shine as an optical quasar.

3 THE ACCRETION OF SMBHS IN SMGS

The GDS04 model predicts the bolometric *intrinsic* time development of AGN activity in forming spheroids. However detailed computations on how and when this activity may show up are made extremely uncertain in most electromagnetic bands by environmental effects. For instance, optical-UV bands are heavily affected by obscuration due both to the general galactic ISM and to that around the very central region. In the IR region, where obscuration is much less a problem, it is however difficult to disentangle dust emission powered by the AGN from that related to SF activity. This is particularly true in our scenario, since the BH growth occurs in a extremely dust-enshrouded ambient, without obvious analogue in the local universe. The situation is more favorable with X-ray photons, especially hard X ones, which are less affected by interactions with the ISM, and are also less likely to be confused with those produced by processes connected with SF, such as X-ray binaries.

Fig. 2 shows number counts (see e.g. De Zotti et al. 1996 for definitions) for SCUBA sources hosting accretion rates onto the central SMBH greater than two interesting thresholds. We predict that about 40% and 15% of SCUBA sources brighter than $\simeq 5$ mJy have $\dot{M}_{BH}$ greater than ~ 0.013 and 0.13 $M_{\odot}$ yr^{-1} respectively (dashed and dot-dashed lines in Fig. 2). With the accretion efficiency 0.15 assumed in the model, and adopting a plausible bolometric correction of $L_{\mathrm{bol}}/L_X[0.5 - 8\mathrm{keV}] \simeq 17$ (Elvis et al 94, Marconi et al. 2004), these values translates to an accretion *intrinsic* luminosity $L_X[0.5 - 8\mathrm{keV}]$ of $\sim 10^{43}$ and 10^{44} erg/s respectively. These figures compare very well with the findings by Alexander et al. (2003, see also Alexander et al. 2005a,b). They found that a fraction $30 - 50\%$ of bright ($\gtrsim 5$ mJy) SCUBA sources hosts mild AGN activity, with X ray (0.5-8 keV) *intrinsic* luminosity between 10^{43} and 10^{44} erg s^{-1}. This fraction raises to $\sim 70\%$ in the radio selected SMG sample studied by Alexander et al. 2005a,b. However they caution that this sample may have an higher incidence of AGN activity than the whole SMG population, due to the condition of radio and spectroscopic identification. Anyway, the observed high fraction of SMGs harboring mild AGN activity indicates that they are accreting constantly, hence supporting the picture presented here.

4 ESTIMATES OF COLUMN DENSITIES

According to our interpretation, the moderate AGN activity revealed by X-ray observations in many bright SCUBA sources corresponds to the build up by accretion of the central SMBH, induced by star formation, and well before the bright QSO phase that causes the end of the major epoch of star formation in these objects.

Alexander et al. (2003, 2005a, 2005b), from the fitting to the X-ray spectra, derive a column density to the central AGN in the range $N_H \sim 10^{20} - 10^{24}$ cm^{-2}, most sources showing $N_H \gtrsim 10^{23}$ cm^{-2}, and a column-density distribution roughly similar to that found for nearby AGNs. Hints on the presence of even Compton-thick absorption in these sources are given by the ~ 1 kev equivalent width Fe Kα emission line seen in the composite X-ray spectrum of the most obscured objects in their sample.

It is interesting to note that, according to our model interpretation, the values of column densities to the nucleus could be dominated by the general ISM of the galaxy alone, rather than by an obscuring torus such as those invoked by unified models for broad lined and narrow lined AGNs. Indeed during the bright SCUBA phase and after a SMBH sufficiently massive to explain the observed intrinsic X-ray luminosities has developed (i.e. BHs with mass in the range $M_{BH} \simeq 5\,10^5 - 10^7$ M$_\odot$ have accretion rates $\dot{M}_{BH} \simeq 0.01-0.1$ M$_\odot$/yr, see Fig. 2), the gas mass in galaxies with $S_{850\mu m} \geqslant 5$ mJy (corresponding to $M_{vir} \gtrsim 2\,10^{12}$ M$_\odot$) is usually enough to produce column densities to the nucleus $N_H \gtrsim$ a few $\times\, 10^{23}$ to a few $\times 10^{24}$. This is the case if the radial density distribution is sufficiently centrally concentrated, such as a typical King profile with core radius $\sim 0.3 - 1$ Kpc (depending on the galaxy mass). However, the precise value of N_H is strongly dependent on the assumed profile. A lower limit is obtained if the gas is more or less uniformly distributed in the galaxy. In this case N_H would drop by 2-3 orders of magnitudes, becoming almost negligible with respect to the observed estimates. Note also that the observed values of N_H, when translated to optical dust absorption adopting a standard conversion factor ($N_H \sim 1.5 \times 10^{21} A_V$), yield large values, consistent with the fact that these AGN are unseen at optical wavelengths.

In GDS04 the fuelling of the central BH in SMGs takes place in two steps: (i) a low-angular momentum gas reservoir is formed, that (ii) then is accreted onto the BH in a timescale set by the Eddington limit (see Sec. 2). Thus the growing BHs may also be hidden by the reservoir. If we assume that its gas is distributed within a region of $\sim 100-200$ pc, i.e. the typical size of the dusty torii explaining the IR SED of type 1 and 2 AGNs (e.g. Granato & Danese 1994), then the N_H we obtain during the SMG phase are between a few 10^{23} to 10^{26} cm^{-2}. These values are again compatible with the observational estimates. If the matter is distributed around the BH in a toroidal-type shape, rather than completely surrounding it, the visibility of the central AGN would depend also on the distribution of the aperture angles.

5 THE MASSES OF SMBHS IN SMGS

Recently, some hydrodynamic simulations of galaxy major mergers incorporated, with sub-grid approximations, the growth of the black hole and its feedback on the evolution of the system (e.g., Di Matteo et al. 2005; Springel et al. 2005). As noticed by Alexander et al. (2005) the black holes of the most massive galaxies in these simulations (which may represent in this merging scenario the SMGs) are up to an order of magnitude more massive than those estimated in SMGs, under the assumption of Eddington limited accretion, and confirmed by the relative narrowness of broad emission lines detected in some sources. These estimates are instead in good agreement with our predictions, at least on average.

This basic difference is due to the fact that in the merging scenario the most active SF phase, corresponding to the final merge, is preceded by a long ~ 1 Gyr phase of disturbance which causes a substantial growth of the SMBH. As a result, when the final merge occurs, the SMBH is already massive enough to immediately accrete all the matter funnelled in its proximity. By converse, in our scenario the SFR reaches levels close to the peak value on a short timescale $\lesssim 0.1$ Gyr, and remains at these levels until the Eddington limited growth of the SMBH, which requires ~ 0.5 Gyr to build up the final mass, ultimately sterilize the system (see Fig 1). Then in this case during most of the "burst" the SMBH is well below its final mass.

Borys et al. (2005) have investigated the relationship between the SMBH and stellar mass in SMGs M_{BH}/M_*, finding values 1-2 orders of magnitude smaller than those of local spheroids with similar masses. They notice that this result may be affected by a few assumptions, and their sample has a modest dynamic range ($\log M_* = 11.4 \pm 0.4$). In our scenario we would expect, during the SMGs phase, an average M_{BH}/M_* of the same order of magnitude as that found by Borys et al, but with a larger dispersion. The observed lack of detected objects with smaller values may be easily accounted for by selections effects, due to the low accretion rate (and possibly high obscuration) of AGN activity in the very early phases. As for the lack of observed SMGs with M_{BH}/M_* closer to the local value, the more obvious possibility is that an important ejection of the dusty ISM begins somewhat earlier than what our schematic model predicts, causing a decrease of the sub-millimeter flux below the current sensitivity in the last 3-4 e-folding times of SMBH growth before the maximum. This would not affect too much the good match with observed SMGs counts, while explaining the lack of sub-millimeter sources with more evolved SMBH. Note also that the reservoir mass increases steadily up to very close to the maximum of the accretion rate (see Fig 1). If this reservoir were responsible for most of the obscuration (see section 4) the last e-folding times of the SMBH growth before the optical QSO shining could be undetectable even in the X-ray band, because the increasing optical depth would overwhelm the increasing intrinsic power. Deeper sub-mm and X-ray data will clarify the issue.

6 X-RAY BACKGROUND AND COUNTS

A detailed prediction of the contribution of forming spheroids and SMBH to X-ray counts and background (XRB), in the context of our model, is a complex issue, involving assumptions not only on the fraction of AGN bolometric luminosity emitted in this spectral region, but also on the (distribution of) absorbing column densities,

which are expected to evolve during the SMBH build-up. As discussed above, we can only attempt an order of magnitude estimate of the range of N_H values from our model, but these values are in agreement with those found by Alexander et al. Thus, to make a crude estimate of the observable X-ray emission, we assume as a reference value of $N_H \sim 3 \times 10^{23}$ cm^{-2}, and we use for our mock objects the X-ray SED defined by Ueda et al. (2003) for AGN with $\log N_H = 23.5$, which includes a Compton reflection bumb, low energy absorbtion and exponential cut-off at 500 keV.

Growing AGN in SCUBA sources may contribute about 20% to the XRB at around 10 keV, where the contribution peaks (Fig. 3). If we include only sub-millimetric sources down to flux limit of $\simeq 1$ mJy, the contribution decreases by more than a factor 2. These figures should be regarded as upper limits, since we expect a fraction of AGN to be affected by column densities larger than those found by Alexander et al. Assuming an higher value $\log N_H = 24.5$ would cause a sharp drop below 10 keV, while the estimate is little affected above this energy, where anyway the contribution decreases.

The predicted X-ray counts due to growing SMBH in forming spheroid are shown in Fig. 4, again adopting $\log N_H = 23.5$. Using $\log N_H = 24.5$ instead, the predicted cumulative counts decrease by a factor ~ 2 at the faint end $< 10^{-15}$ erg cm^{-2} s^{-1}, where in any case they could provide a sizeable fraction of sources (a few tens percent).

7 SUMMARY AND CONCLUSIONS

We added support to the idea that the *mutual* relationship between the formation of spheroids and the AGN activity is a key ingredient that *must* be included into models of galaxy formation. The prescriptions of our ABC scenario (Granato et al. 2001, 2004) lead to predictions in general agreement with many observations. Here we concentrated on X-ray properties of SMGs, which support one of its basic ingredients, namely the SF promoted growth of a SMBH. Constraints on model details in the final phase of this growth are expected from deeper sub-mm and X-ray observations.

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